

SPECTROSCOPIC CONFIRMATION OF A SUBSTANTIAL POPULATION OF LUMINOUS RED GALAXIES AT REDSHIFTS $z \gtrsim 2$ ^{1,2}

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ABSTRACT

We confirm spectroscopically the existence of a population of galaxies at $z \gtrsim 2$ with rest-frame optical colors similar to normal nearby galaxies. The galaxies were identified by their red near-infrared colors in deep images obtained with ISAAC on the Very Large Telescope of the field around the foreground cluster MS 1054–03. Redshifts of six galaxies with $J_s - K_s > 2.3$ were measured from optical spectra obtained with the W. M. Keck Telescope. Five out of six are in the range $2.43 \leq z \leq 3.52$, demonstrating that the $J_s - K_s$ color selection is quite efficient. The rest-frame ultraviolet spectra of confirmed $z > 2$ galaxies display a range of properties, with two galaxies showing emission lines characteristic of AGN, two having Ly α in emission, and one showing interstellar absorption lines only. Their full spectral energy distributions are well described by constant star formation models with ages 1.4 – 2.6 Gyr, except for one galaxy whose colors indicate a dusty starburst. The confirmed $z > 2$ galaxies are very luminous: their K_s magnitudes are in the range 19.2 – 19.9, corresponding to rest-frame absolute V magnitudes -24.8 to -23.2 . Assuming that our bright spectroscopic sample is representative for the general population of $J_s - K_s$ selected objects, we find that the surface density of red $z \gtrsim 2$ galaxies is $\approx 0.9 \text{ arcmin}^{-2}$ to $K_s = 21$. The surface density is comparable to that of Lyman-break selected galaxies with $K_s < 21$, when corrections are made for the different redshift distributions of the two samples. Although there will be some overlap between the two populations, most “optical-break” galaxies are too faint in the rest-frame ultraviolet to be selected as Lyman-break galaxies. The most straightforward interpretation is that star formation in typical optical-break galaxies started earlier than in typical Lyman-break galaxies. Optical-break galaxies may be the oldest and most massive galaxies yet identified at $z > 2$, and could evolve into early-type galaxies and bulges.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation

1. INTRODUCTION

The identification of star-forming galaxies at $z \gtrsim 3$ by the Lyman-break technique has greatly enhanced our understanding of galaxy formation and the star formation history of the universe (Steidel et al. 1996, 1999; Madau et al. 1996). Although other high redshift galaxy populations have since been identified (e.g., Hu, Cowie, & McMahon 1998; Smail et al. 2000; Barger et al. 2001), Lyman-break galaxies (LBGs) dominate the UV luminosity density at high redshift (Steidel et al. 1999), and have been argued to be the progenitors of massive galaxies in groups and clusters (e.g., Baugh et al. 1998).

However, the census of normal galaxies at $z \sim 3$ may still be incomplete because of selection effects. The Lyman-break technique requires a high rest-frame far-ultraviolet (UV) luminosity, and so will preferentially select relatively unobscured, actively star-forming galaxies. Stellar ages of LBGs are typically $\sim 3 \times 10^8$ yr (Papovich, Dickinson, & Ferguson 2001; Shapley et al. 2001), suggesting that the descendants of galaxies which started forming stars at significantly higher redshift ($z > 4$) may be underrepresented in current surveys (e.g., Fer-

guson, Dickinson, & Papovich 2002).

As shown in a companion paper (Franx et al. 2003) such “evolved” high redshift galaxies can be selected effectively in the rest-frame optical, which is redshifted to near-infrared (NIR) wavelengths for $z \gtrsim 2$. The criterion $J_s - K_s > 2.3$ is expected to select galaxies with prominent rest-frame optical breaks, caused by the 3625 Å Balmer-break or the 4000 Å Ca II H+K break.¹⁰ This “optical-break” selection is complementary to the ultraviolet Lyman-break selection. In Franx et al. (2003) we show that optical-break galaxies have a high surface density in Hubble Deep Field South (HDF-S), and derive from photometric redshifts that their volume density is comparable to LBGs. In Daddi et al. (2003) we infer that the population is highly clustered. The main uncertainties in Franx et al. are the lack of spectroscopic redshifts and the small $2'3 \times 2'3$ field.

Here we present spectroscopic observations of a small sample of optical-break galaxies in MS 1054–03, a field with a foreground cluster at $z = 0.83$. The NIR imaging data in this field complement our extremely deep Very Large Telescope (VLT) ISAAC data on HDF-S (Labbé et al. 2003), and consist of

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¹⁰ Magnitudes are on the Vega system, unless stated otherwise.

77.5 hours of J_s, H, K_s imaging with ISAAC distributed over a 5.4×5.4 square of four pointings (Förster Schreiber et al., in preparation). Although not as deep as our HDF-S observations, the ~ 5 times larger area enables a more robust measurement of the surface density and is well suited for efficient multi-slit spectroscopy.

2. SPECTROSCOPY

Optical spectroscopy was obtained for galaxies in the MS 1054–03 field on 2002 February 14–17 with the Low Resolution Imaging Spectrograph (Oke et al. 1995) on the W. M. Keck telescope. The sample was not restricted to $J_s - K_s$ selected galaxies, but also contained candidate $1 < z < 2$ galaxies selected by their red $I - H$ color. The sample was limited at $K = 20.7$, with priority given to objects with $I < 24.5$. Four multi-slit masks were designed, with faint objects repeated in several or all masks. The 300 lines mm^{-1} grism was used on the blue arm, in combination with the D680 dichroic. On the red arm we used the 600 lines mm^{-1} grating ($1 \mu\text{m}$ blaze) on February 14–15 and the 400 lines mm^{-1} grating (8500 \AA blaze) on February 16–17. Conditions were photometric and the seeing ranged from $0''.8$ to $1''.5$. The exposure time ranged from 7.2 ks for the brightest objects to 72 ks for the faintest.

Redshifts were measured for six out of eleven observed $J_s - K_s$ selected galaxies. Five have redshifts in the range 2.43–3.52, with the remaining galaxy showing a faint emission line which we tentatively identify as [O II] 3727 \AA at $z = 1.19$ (Table 1). Additionally, redshifts were measured for twelve out of 27 observed galaxies with $I - H > 3.0$ and $J_s - K_s < 2.3$; they are in the range 1.06–1.87, with mean $\langle z \rangle = 1.40$.

The spectroscopic redshifts confirm that our simple $J_s - K_s$ color cut effectively isolates galaxies at $z > 2$, indicating only a small ($\sim 20\%$) contamination by (dusty) galaxies at lower redshifts. A concern is that the five $J_s - K_s$ selected galaxies without redshift are at $z \sim 1.5$, as there would be no strong spectral features in the observed wavelength range. The importance of this potential bias can be estimated by comparing the photometric redshifts of galaxies with and without spectroscopic redshift. Photometric redshifts were determined using the publicly available HYPERZ code (Bolzonella, Miralles, & Pelló 2000); a full discussion is given in Förster Schreiber et al., in preparation. As demonstrated in Fig. 1 the photometric and spectroscopic redshifts are in good agreement. The red histogram shows the photometric redshift distribution of the five $J_s - K_s$ selected galaxies without spectroscopic redshift. Two are in the range $1.7 < z_{\text{phot}} < 2$, and three have $z_{\text{phot}} > 2$. The median is 2.4, similar to the median photometric redshift of galaxies with spectroscopic redshifts (2.6). We conclude that there is no evidence for a strong redshift bias in our spectroscopic sample.

The redshifts of the five confirmed $z > 2$ galaxies span a large range, which is not surprising given the large spacing between the J_s and K_s filters. The mean redshift is 2.7, similar to the median photometric redshift of 2.6 for galaxies with $J_s - K_s > 2.3$ and $K_s < 22.5$ in HDF-S (Franx et al. 2003). Remarkably, three galaxies are at almost identical redshift, qualitatively consistent with the strong angular clustering of $J_s - K_s$ selected galaxies in HDF-S (Daddi et al. 2003).

The $J_s - K_s$ selection is the higher redshift analog of the well known selection of $1 < z < 2$ galaxies by their $I - H$ color (e.g., McCarthy et al. 2001), and by combining the two methods galaxies can be selected over the entire range $1.0 \lesssim z \lesssim 3.5$

(see Fig. 1). We note that $I - H$ selected galaxies appear to be highly clustered as well: only one out of twelve objects is *not* within 2000 km s^{-1} of another galaxy.

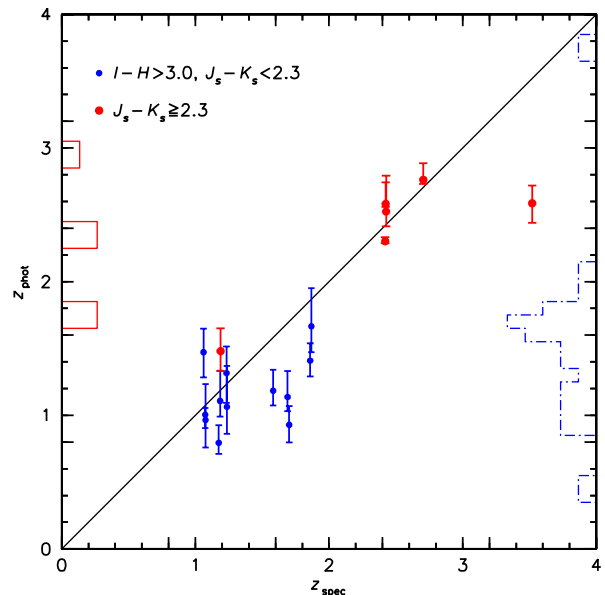


FIG. 1.— Spectroscopic and photometric redshifts of galaxies selected by broadband colors. The twelve galaxies with $I - H > 3.0$ and $J_s - K_s < 2.3$ have redshifts in the range 1.06–1.87. Five out of six galaxies with $J_s - K_s > 2.3$ are at $2.43 \leq z \leq 3.52$. Histograms show the photometric redshifts of observed galaxies whose spectra had insufficient S/N to determine their spectroscopic redshifts.

TABLE 1
 $J_s - K_s$ SELECTED GALAXIES WITH REDSHIFTS

Galaxy	K_s	$K_{s,\text{corr}}^a$	$J_s - K_s^b$	z	$M_{V,\text{rest}}^c$
596	19.68	19.91	2.35	1.189	—
1671	19.09	19.23	2.65	2.424	−23.7
1195	19.29	19.63	2.30	2.425	−23.9
1458	19.71	19.86	2.25	2.427	−23.2
184	19.29	19.40	2.54	2.705	−24.1
1656	19.59	19.81	2.98	3.525	−24.8

^a K -band magnitudes corrected for weak lensing amplification by the foreground $z = 0.83$ galaxy cluster (Hoekstra, Franx, & Kuijken 2000).

^b Colors were recalibrated following the initial spectroscopic selection; errors are ≈ 0.05 magnitudes.

^c $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

3. SPECTRA OF RED $z > 2$ GALAXIES

The rest-frame UV spectra of confirmed $z > 2$ galaxies are shown in Fig. 2. The small sample displays a wide range of properties: two galaxies have emission lines characteristic of Active Galactic Nuclei (AGN), two are Ly α emitters with no evidence for the presence of an AGN, and one shows interstellar absorption lines typical of nearby star-forming galaxies.

The high fraction of emission line galaxies is striking, although in part a selection effect resulting from the difficulty of measuring absorption line redshifts of these faint galaxies. Our single absorption redshift required an exposure time of 72 ks, and judging from a cross-correlation with a LBG template it is only marginally significant ($r = 3.1$). Two other galaxies show

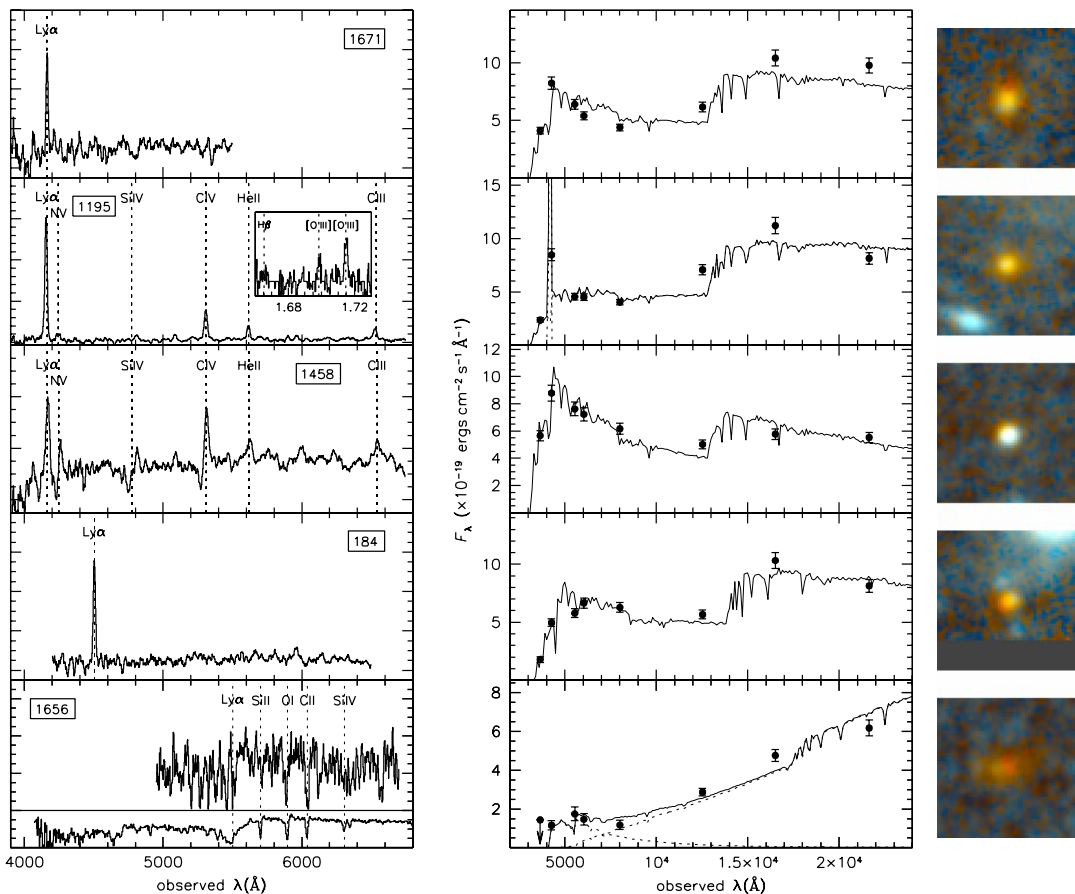


FIG. 2.— *Left panels:* Rest-frame UV spectra of galaxies at $z > 2$. The spectra display a wide range of properties. The inset for galaxy 1195 shows a NIRSPEC rest-frame optical spectrum. The panel below 1656 shows the mean spectrum of ~ 250 Lyman-break galaxies without $\text{Ly}\alpha$ emission, from Shapley et al. (2002, in preparation). *Right panels:* Spectral energy distributions of the same galaxies. Overplotted are models with varying age and dust content (see text). The B_H , and probably J_s band fluxes of 1195 are affected by strong emission lines. Color images were created from the $HST R_{AB} \equiv 0.5 \times (V_{F606W}^{AB} + I_{F814W}^{AB})$ and VLT K_s images (after smoothing to the same resolution), and are $5''.1 \times 5''.1$.

evidence for breaks indicating the onset of the $\text{Ly}\alpha$ forest, but do not produce significant peaks in their cross-correlation functions. Since there are five observed galaxies without redshift we estimate that the true emission line fraction is $\gtrsim 40\%$. The fact that $\text{Ly}\alpha$ photons can escape in some $J_s - K_s$ selected galaxies may indicate that they are not all very dusty, or that they have patchy dust distributions.

The two AGN are at identical redshift and separated by $84''$. Galaxy 1195 is a narrow-line AGN similar to Type-II quasars and nearby Seyfert-II galaxies. Galaxy 1458 has a complex spectrum, with narrow ($\sim 1500 \text{ km s}^{-1}$ FWHM) $\text{Ly}\alpha$ and C IV emission lines and broader ($\sim 3000 \text{ km s}^{-1}$) He II and C III lines. The resonant transitions N V, Si IV, and C IV show P-Cygni profiles, indicative of a radiatively driven $\sim 3000 \text{ km s}^{-1}$ wind (e.g., Murray et al. 1995). More data are needed to determine how common AGN are among $J_s - K_s$ selected galaxies, and to compare the rate of occurrence to that in rest-UV selected objects (Steidel et al. 2002). It is widely believed that all massive, bulge-dominated systems in the local universe harbor massive black holes (e.g., Magorrian et al. 1998) and we can speculate that the optical-break galaxies are progenitors of such galaxies observed at a time when many black holes were still in the process of formation.

4. SPECTRAL ENERGY DISTRIBUTIONS

Broad band spectral energy distributions (SEDs) are shown in the central panels of Fig. 2. Optical data were obtained with the *Hubble Space Telescope* (HST) WFPC2 (van Dokkum et al. 2000) and VLT+FORs; a full description of the photometry is given in N. M. Förster Schreiber et al. (in preparation). We fitted GISEL98 model spectra from Bruzual & Charlot (in preparation) to interpret the SEDs. As is well known it is difficult to obtain unique solutions for the functional form of the star formation history, the age of the stellar population, and the dust content (see, e.g., Papovich et al. 2001; Shapley et al. 2001). Here we only consider models with constant star formation rate and a Calzetti et al. (2000) reddening law.

As shown in Fig. 2 the two $\text{Ly}\alpha$ emitting galaxies 1671 and 184 are fairly well fitted by such models. The same model with a “maximally old” age of 2.6 Gyr and moderate extinction $E(B - V) = 0.4$ provides the best fit to both galaxies, and we conclude that the red $J_s - K_s$ colors of these objects are most likely the result of their evolved stellar populations. The SEDs of galaxies 1195 and 1458 are almost certainly affected by emission from their AGN, which is difficult to model. When the continuum contributions of the AGN are ignored, galaxy 1458 is best fitted by a constant star formation model of age

1.4 Gyr and $E(B - V) = 0.3$, and 1195 by a model with age 1.7 Gyr and $E(B - V) = 0.5$. The highest redshift galaxy in our sample, 1656, is not well fitted by simple models. Good fits are obtained for composite models of a young, dust-free component and a second young component which is heavily obscured, having $E(B - V) \sim 1.5$ (see Fig. 2).

For galaxy 1195 the contribution of Ly α emission to the B -band flux (30–40%) had to be taken into account in the model fitting. On January 6 2002 we obtained a 1200 s H -band spectrum with NIRSPEC on Keck II (inset in Fig. 2). The spectrum shows the redshifted [O III] λ 4959, 5007 lines; H β is undetected. The lines contribute 0.12 ± 0.04 magnitudes to the H -band flux, consistent with the observed offset from the best fitting model spectrum. Since 1195 is by far the strongest Ly α emitter in our sample this result suggests that the contribution of line emission to the NIR fluxes is generally small for $J_s - K_s$ selected galaxies.

We conclude that the red $J_s - K_s$ colors are probably produced by evolved stellar populations and in one case a dusty young population. The median age of 1.7 Gyr is higher than the median age of $\sim 3 \times 10^8$ yr of LBGs, derived using the same models (Shapley et al. 2001; Papovich et al. 2001).

5. DISCUSSION

The spectroscopic redshifts demonstrate that $z \gtrsim 2$ galaxies can be selected efficiently by $J_s - K_s$ colors alone. The criterion $J_s - K_s > 2.3$ is not extreme, but selects galaxies whose rest-frame optical colors are similar to those of normal nearby galaxies: for $z = 2.7$ our $J_s - K_s$ limit corresponds to $U - V \gtrsim 0.1$ in the rest-frame, and a local sample selected thus would include almost all luminous galaxies (e.g., Jansen et al. 2000).

The surface density of $J_s - K_s > 2.3$ galaxies in the MS 1054–03 field is $1.09^{+0.20}_{-0.16}$ arcmin $^{-2}$ to $K = 21$. If our small spectroscopic sample is representative for the general population, $\sim 20\%$ are at low redshift, and the surface density of $z > 2$ optical-break galaxies is ≈ 0.9 arcmin $^{-2}$ (ignoring the lensing effect of the foreground cluster). The Poissonian errors imply 65% confidence limits of 0.7 – 1.1. However, significant field-to-field variations exist: there are no $J - K > 2.3$ galaxies to $K = 21$ in HDF-N (Fernández-Soto, Lanzetta, & Yahil 1999), whereas the surface density in HDF-S is similar to that in the $\sim 5\times$ larger MS 1054–03 area. Additional errors due to galaxy correlations increase the upper limits, but leave the lower limits relatively unchanged (see, e.g., Daddi et al. 2000). Based on the observed clustering of $J_s - K_s > 2.3$ galaxies in HDF-S (Daddi et al. 2003), we find a 2σ lower limit of ≈ 0.5 arcmin $^{-2}$.

The surface density can be compared to that of LBGs with $K_s \leq 21$, by integrating the K_s -band luminosity function determined for $z \approx 3$ LBGs by Shapley et al. (2001). We assume that the luminosity function does not evolve, and use a template spectrum to calculate the dependence of M_K^* on redshift. Integrating over the redshift range 2.0 – 3.5 we find a surface den-

sity of ≈ 2.0 arcmin $^{-2}$ to $K_s = 21$, twice the density of optical-break galaxies. This result is quite sensitive to the assumption that the redshift distribution of optical-break galaxies is a tophat with a lower bound of 2.0. Integrating over the redshift range 2.4 – 3.5 reduces the density to ≈ 0.9 arcmin $^{-2}$, and we conclude that the surface density of optical-break selected galaxies is $0.5 - 1\times$ that of Lyman-break selected galaxies in the same redshift range. These numbers are broadly consistent with results obtained for fainter samples in HDF-S (Franx et al. 2003).

Optical-break galaxies are underrepresented in samples selected by the Lyman-break technique: only two out of 40 galaxies observed in J and K_s by Shapley et al. (2001) satisfy our selection criterion. Most optical-break galaxies in the MS 1054–03 field are too faint in the rest-frame UV to be selected as LBGs in ground-based surveys: $\sim 70\%$ of galaxies with $K_s < 21$ have $R_{AB} > 25.5$. As shown in Franx et al. (2003) the overlap is even smaller for the fainter HDF-S sample. We note however that – because of obvious selection effects – four of the five galaxies confirmed by optical spectroscopy are brighter than this limit, and probably would be selected as LBGs if at the appropriate redshift.

The most straightforward (but not unique) interpretation of the newly identified population is that they are evolved descendants of galaxies that started forming stars at redshifts $z > 4$. As shown in Franx et al. (2003) their typical mass-to-light ratios are probably higher than those of galaxies selected by the Lyman-break technique; hence they may be the most massive galaxies yet identified at $z > 2$, and could be progenitors of early-type galaxies and bulges. Interestingly, the five confirmed $z > 2$ galaxies alone may already place limits on galaxy formation models. They constitute $\approx 1.5\%$ of the $K_s < 20$ counts (e.g., Maihara et al. 2001, Labbé et al. 2002), whereas current semianalytical galaxy formation models have predicted that galaxies beyond $z \sim 2$ should essentially be absent in such bright samples (see Cimatti et al. 2002). The fraction is even higher ($\sim 5\%$) when galaxies without spectroscopic redshift are included.

Surveys over larger areas will help establish the surface density with greater confidence. More spectroscopy is needed to determine the redshift distribution and AGN fraction better. Finally, NIR spectroscopy for more galaxies is needed to determine the contribution of emission lines to the broad band fluxes.

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